COAL-WATER MIXTURE COMBUSTION USING OXYGEN-ENRICHED AIR AND STAGED FIRING

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ABSTRACT

Coal-water mixture (CWM) combustion experiments using oxygen-enriched air were conducted in an oil-designed 700-hp watertube boiler using a bituminous CWM. The results indicated that the use of oxygen-enriched air increased carbon burnout, reduced uncontrolled fly ash emissions, and reduced combustion air preheating requirements. The boiler efficiency increased because of reduced flue gas heat losses. The improvement in boiler performance compared to an experiment without oxygen enrichment was significant when using only 2-3 percent enrichment of air (23-24 volume percent oxygen). Using combustion air enriched to 22.7 percent oxygen by volume, the required air preheating temperature was reduced to 192°F as compared to 325°F required with no oxygen enrichment, while the carbon conversion efficiency at full boiler load was increased from 95.0 percent to 97.4 percent.

Experiments on CWM combustion were also conducted using staged firing with and without oxygen-enriched air. The NO_x reduction achieved at a first-stage air/fuel stoichiometric ratio of 0.76 was about 33 percent, but it was accompanied by a reduction in combustion efficiency and an increase in particulate emissions. The use of oxygen-enriched air in the burner zone increased flame stability and carbon burnout while maintaining the effectiveness of staged combustion; however, additional experiments are needed to optimize burner-operating parameters to achieve significant NO_x reduction.

INTRODUCTION

The use of oxygen-enriched air for coal-water mixture (CWM) combustion could result in several positive effects on boiler performance: (1) preheated air requirements should be reduced or eliminated, thereby permitting the use of CWM in smaller industrial boilers that do not usually have high-temperature air preheaters; (2) the volume and velocity of the flue gas will be reduced, decreasing potential erosion problems in the boiler convection banks; and (3) boiler efficiency should increase because of reduced stack heat losses, partially compensating for loss in boiler efficiency owing to water in the slurry. Taschler et al. examined the impact of these effects on boiler operating economics and steam generation capacity in large-scale boilers (1).

Coal-water mixture combustion experiments using oxygen-enriched air were conducted at Pittsburgh Energy Technology Center (PETC) in a 700-hp watertube boiler using a commercial CWM fuel prepared from bituminous coal. The objectives of these tests were to determine (1) the optimal point of oxygen injection, (2) the minimal oxygen concentration required to stabilize the CWM flame without preheating the combustion air, and (3) the effects of boiler load conditions on oxygen enrichment requirements.

The CWM combustion experiments were also conducted using staged firing with and without oxygen-enriched air. Staged combustion is one of the most commonly applied NO_x-control techniques for coal-fired boilers (2-4). The boiler is operated with a primary fuel-rich combustion zone, in which both thermal and fuel NO_x formation is minimized. The initial combustion step is then followed by a

fuel-lean zone to complete the combustion of the residual fuel. Staged combustion in the PETC boiler was achieved by introducing the first-stage air through the burner air register, and the second-stage air through three air ports installed on a side wall of the boiler.

EXPERIMENTAL

The test unit is a Nebraska 700-hp "D"-type watertube industrial boiler originally designed for No. 6 oil firing. The boiler generates about 24,000 lb/hr of steam at full load. Figure 1 is a sectional plan view through the firebox and convection section of the boiler. Preheated combustion air is provided by an external source. The Coen single-air-zone register provided with the boiler was modified for these experiments. One of two modifications made to the air register was a diameter change of the sheet metal shroud, which increased the secondary-air linear velocities at the exit throat of the register. The other simple change was the insertion of a center air tube to establish a stable flame front. The center tube has a fixed air spinner, and both the center-tube-air and secondary-air feeds have independent flow-control systems. This allows considerable flexibility in burner-operating capabilities (5). Extensive instrumentation and a computer-controlled data acquisition system provide a large amount of data for detailed analysis and evaluation of the experiments.

Tertiary (second-stage) air is injected through three ports installed at approximately one third of the furnace length from the front wall. The port design incorporates removable sleeves to allow changing of port size to permit control of the second-stage air flow and the injection pattern.

Figure 2 is a cross-sectional view of the burner used for oxygen-enrichment tests. Oxygen is introduced through a specially fabricated oxygen guide tube (3 1/2-inch schedule-10 Monel pipe) surrounding the burner-gun guide tube. A Coen nozzle with eight 15/64-inch holes and a 60° spray angle was used. A 30° cocurrent center-air diffuser and a 45° cocurrent oxygen-guide-tube diffuser were installed during the combustion experiments.

CWM COMBUSTION USING OXYGEN-ENRICHED AIR

The use of oxygen-enriched combustion air reduces the amount of nitrogen flowing through a combustion process, resulting in elevated flame temperatures. Figure 3 shows adiabatic flame temperatures for the combustion of CWM with oxygen-enriched air at an oxygen/fuel stoichiometric ratio of 1.15. Theoretical flame temperature curves were generated at combustion air preheating temperatures of 77° (ambient), 300°, and $500^\circ F$ using the PETC Multiphase Equilibrium Program for a CWM containing 70 percent Pittsburgh seam bituminous coal. The adiabatic flame temperature using normal air ($O_2 = 20.69$ volume percent) preheated to $500^\circ F$ is $3393^\circ F$; the same flame temperature can be achieved by using 23.25 volume percent oxygen-enriched air at ambient temperature.

Because of the reduction in the amount of nitrogen per unit quantity of fuel flowing through the furnace, the amount of flue gas from the combustion of CWM using oxygen enrichment will be decreased. The decrease in flue gas volume, expressed in standard cubic feet per pound of CWM (at $70^\circ F$ and 14.7 psia), is illustrated in Figure 4. For example, at 23 volume percent and 25 volume percent oxygen concentrations in the combustion air, and an oxidizer/fuel stoichiometric ratio of 1.15, the flue gas quantities decrease by 8 percent and 15 percent, respectively, compared to the quantity produced when using normal air.

Oxygen enrichment should reduce combustion air preheat requirements and reduce flue gas heat losses. Oxygen enrichment should also provide a greater range of flammability and improved flame stability compared to combustion air pre-heating.

A commercial CWM, ARC-COAL, produced by the Atlantic Research Corporation and containing 70 percent Eastern U.S. bituminous coal, was used in the oxygen enrichment experiments (see Table 1). Analysis of the experimental results indicates that the addition of oxygen to the combustion air results in higher carbon conversion and boiler efficiencies. Using 500°F combustion air at an oxygen level equivalent to 22.9 percent by volume in air, a carbon conversion efficiency of 97.0 percent and a boiler efficiency of 81.3 percent were obtained (see test 2 in Table 2). The base-line test (test 1) at 500°F preheating without oxygen enrichment resulted in 95.0 percent carbon conversion and 79.3 percent boiler efficiency. Because of the improvement in carbon burnout with oxygen enrichment, the carbon content of the fly ash decreased by more than 25 percent (Table 3). As a consequence, particulate emissions were also reduced. With oxygen enrichment, however, NO_x emissions increased from 0.69 to 1.00 lb NO_2/MMBtu (tests 1 and 2 in Table 3). The increased flame temperature due to oxygen enrichment apparently increased the formation of thermal NO_x.

Test 3 of Tables 2 and 3 was conducted at reduced boiler load (~70 percent of maximum capacity) using oxygen-enriched air. A slight improvement (1%) in carbon conversion was obtained compared to test 2, which was conducted at full load.

Test 4 was carried out at full load and at minimum combustion air preheat temperature (192°F) using 22.7 percent oxygen-enriched air. An improvement in boiler performance compared to the test without oxygen enrichment (test 1) is noticeable, even though the preheating temperature was reduced substantially. The minimum combustion air preheating required for a stable flame is affected by a number of variables, including CWM volatility, heating value, and oxygen enrichment (flame temperature). Other variables, such as excess oxygen level and combustion air swirl, are also important. With increased oxygen concentration in the oxygen-enriched air, the combustion air flow per unit quantity of fuel at a constant oxidizer/fuel ratio is reduced. This would reduce the intensity of the combustion air swirl and possibly adversely affect the flame stability.

CWM COMBUSTION USING STAGED FIRING

Combustion experiments were conducted at full boiler load and at total air/fuel stoichiometric ratios of 1.15 to 1.21 using combustion air preheated to about 490°F (see Tables 4 and 5). Stoichiometric ratios of the first-stage air (atomizing air plus center-tube air plus secondary air) to fuel were varied between 0.76 and 0.97 while the remaining air (tertiary air) was diverted through the side wall ports. Boiler operation could not be sustained at a stoichiometric ratio less than 0.75 in the primary combustion zone because of flame instabilities.

A base-line experiment performed without air staging (with the tertiary air ports blocked) produced NO_x emission levels of 0.77 lb/MMBtu (see test 1, Tables 4 and 5). As primary-zone stoichiometry was reduced, emissions of NO_x declined; the NO_x reduction achieved with the primary-zone stoichiometry of 0.76 was about 33 percent. The reduction in NO_x emissions, however, was achieved with some decrease in combustion efficiency. As the first-stage stoichiometric ratio was reduced from 1.15 to 0.76, the carbon conversion efficiency decreased from 95.7 percent to 92.2 percent.

It is apparent that the conditions created by deep staging (primary zone stoichiometry of less than 0.75) tend to be opposite of those conducive to good flame stability and high carbon-conversion efficiencies. Improvements in combustion efficiency may be attainable by changing the tertiary-air port location and/or velocity to increase the efficiency of tertiary-air mixing in the second stage. However, because of limitations in primary-zone temperature and residence time, it may be difficult to achieve large reductions in NO_x emissions while

firing coal or CWM in an oil-designed boiler without exacerbating the problem of fuel burnout.

CWM COMBUSTION USING STAGED FIRING AND OXYGEN-ENRICHED AIR

One approach to increasing the primary-zone temperature, flame stability, and carbon burnout under deep-staging conditions is to use oxygen-enriched air. Tables 6 and 7 show the results of CWM combustion experiments using both staged firing and oxygen-enriched air. Oxygen was introduced into the primary combustion zone through the burner oxygen guide tube (see Figure 2). These experiments were conducted using 356°F to 413°F combustion air at 1.14 to 1.16 overall oxygen/fuel stoichiometric ratio and at an overall oxygen concentration of about 26 percent by volume. Carbon conversion efficiencies ranging from 95.6 percent to 97.8 percent and boiler efficiencies ranging from 81.0 percent to 82.8 percent were obtained as the oxygen/fuel stoichiometric ratio in the primary combustion zone was varied from 1.14 (unstaged) to 0.76.

Carbon conversion efficiency was reduced only slightly and the boiler efficiency remained high as the degree of staging increased. However, a reduction in NO_x emissions was observed when the primary-stage stoichiometry was reduced to 0.76, as shown in Figure 5. With oxygen enrichment, the measured NO_x emissions at all primary-stage stoichiometries were higher than those measured in experiments conducted with no oxygen enrichment, even though the oxidizer was preheated to a higher temperature in the latter experiments.

These results suggest that the problem of reduced carbon burnout in staged combustion can be alleviated with the use of oxygen-enriched air in the burner zone while achieving a moderate reduction in NO_x emissions. However, even the experiment that provided the greatest reduction in NO_x emissions resulted in levels that are quite high (>0.6 lb NO_2/MMBtu). To further reduce NO_x emissions, it would be necessary to decrease the primary-stage stoichiometry (for this furnace, to less than 0.76). Additional experiments are required to determine if a significant reduction of NO_x emissions can indeed be achieved using oxygen-enriched air in a staged combustion system while maintaining a high level of carbon conversion efficiency.

CONCLUDING REMARKS

The combustion experiments conducted in the 700-hp watertube boiler with bituminous CWM indicate that the use of oxygen-enriched air resulted in a decrease in the level of air preheating required and an improvement in carbon burnout. The reduction in the volume of flue gas lowered heat losses and increased boiler efficiency. Using combustion air enriched to 22.7 percent oxygen by volume, the air preheating temperature could be reduced to 192°F as compared to ~325°F required with no oxygen enrichment. The improvement in boiler performance compared to the test without oxygen enrichment was noticeable even with the use of only 2-3 percent enrichment of air (23-24 volume percent oxygen).

By using staged air admission during CWM combustion in the oil-designed boiler, a reduction in NO_x emissions on the order of 1/3 was achieved. The reduction in NO_x emissions, however, was achieved with some decrease in combustion efficiency. Using 490°F combustion air at 15-21 percent excess, as the primary-stage stoichiometry was reduced from 1.15 to 0.76, NO_x emissions decreased from 0.77 lb/MMBtu to 0.52 lb/MMBtu while the carbon conversion efficiency decreased from 95.7 percent to 92.2 percent.

The use of oxygen-enriched air in the primary combustion stage increased the flame stability and diminished the problem of reduced carbon burnout while achieving moderate reduction of overall NO_x emissions. Using 356°F to 413°F combustion air at 14-16 percent excess and at an overall oxygen concentration of about 26

volume percent, NO_x emissions decreased from 0.88 lb/MMBtu to 0.65 lb/MMBtu as the primary-stage stoichiometry decreased from 1.14 to 0.76. The carbon conversion and boiler efficiencies, however, remained high and were in the ranges of 96-98 percent and 81-83 percent, respectively.

DISCLAIMER

Reference in this paper to any specific commercial product, process, or service is to facilitate understanding and does not necessarily imply its endorsement or favoring by the United States Department of Energy.

REFERENCES

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Table 1. Typical Analyses of ARC-Coal

	As Received	Dry Basis
Weight Percent Coal	70.59	
Particle Size Consist (% minus-200-mesh)	89	
Proximate Analysis (%)		
Moisture	29.41	--
Volatile Matter	22.40	31.73
Fixed Carbon	42.81	60.65
Ash	5.38	7.62
Ultimate Analysis (%)		
Hydrogen	6.82	5.04
Carbon	56.86	80.53
Nitrogen	1.08	1.53
Sulfur	0.53	0.75
Oxygen	29.33	4.53
Ash	5.38	7.62
Heating Value (Btu/lb)	10,140	14,365
Viscosity (cP @ 100 sec^{-1} after 50 seconds, 79°-81°F)	584	
Ash Fusion Temperatures (°F)		
Initial Deformation Temp.	2580	
Softening Temp.	2670	
Fluid Temp.	2700	

Table 2. Operating Conditions and Boiler Performance,
CWM Tests with Oxygen Enrichment

Test Number	1	2	3	4
O_2 Vol. % in Comb. Air	20.69	22.91	22.83	22.68
Overall Oxygen/Fuel Stoichiometric Ratio	1.16	1.15	1.14	1.25
O_2 Injected (lb/hr)	0	598	385	618
Fuel Flow (lb/hr)	2791	2733	1843	2833
Steam Flow (lb/hr)	24250	24390	16540	24010
Thermal Input (MMBtu/hr)	30.20	29.22	19.67	30.04
Combustion-Air Temp. (^{O}F)	501	491	490	192
Total Air Flow (lb/hr)	24656	21423	14379	25052
Atomizing-Air Flow (lb/hr)	1287	1316	1312	1338
Atomizing-Air Pressure (psig)	128	126	129	130
Fuel Pressure at Burner (psig)	109	105	88	148
Center-Tube-Air Flow (lb/hr)	4910	4749	4516	5804
Avg. Flue Gas Temp. (^{O}F)	500	509	463	503
Carbon Conversion Eff. (%)	95.0	97.0	98.1	97.4
Boiler Eff. (%) (Heat Loss Method)	79.3	81.3	82.2	80.0
Heat Loss Due to H_2O in Fuel (%)	3.21	3.26	3.21	3.24
Heat Loss from Burning Hydrogen in Fuel (%)	3.74	3.79	3.74	3.95

Table 3. Flue Gas Emissions in CWM Tests
with Oxygen Enrichment

Test Number	1	2	3	4
Flue Gas Analysis				
O_2 (%)	2.9	3.1	3.9	4.2
CO_2 (%)	15.1	17.1	16.2	15.7
CO (ppm)	72	50	55	51
SO_2 (ppm)	646	693	667	662
(lb/MMBtu)	1.24	1.20	1.24	1.23
NO_x *(ppm)	499	800	753	703
(lb/MMBtu)	0.69	1.00	1.00	0.94
THC (ppm)	1.7	0.8	1.0	3.0
Particulate Emissions (Uncontrolled)				
(lb/hr)	168	133	45	124
(lb/MMBtu)	6.07	4.91	2.49	4.26
C in Fly Ash (%)	46.6	34.6	41.4	33.9

*As ppm of NO + ppm of NO_2; calculated as lb of NO_2/MMBtu.

Table 4. Operating Conditions and Boiler Performance,
CWM Tests with Staged Combustion

Test Number	1	2	3	4
Total Air/Fuel Stoichio-metric Ratio	1.15	1.20	1.21	1.15
First-Stage Air/Fuel Stoichiometric Ratio	1.15	0.97	0.85	0.76
Fuel Flow (lb/hr)	2888	2969	2940	3026
Steam Flow (lb/hr)	23990	24630	24080	24000
Thermal Input (MMBtu/hr)	30.74	31.77	31.45	32.40
Combustion-Air Temp. (^{O}F)	491	490	481	494
Total Air Flow (lb/hr)	25380	27170	27210	26460
Secondary-Air Flow (lb/hr)	17740	15360	13300	12110
Center-Tube-Air Flow (lb/hr)	6096	5340	4682	4122
Tertiary-Air Flow (lb/hr)	--	5264	8046	8985
Atomizing-Air Flow (lb/hr)	1164	1206	1182	1243
Atomizing-Air Pressure (psig)	127	126	129	125
Fuel Pressure at Burner (psig)	114	119	117	124
Avg. Flue Gas Temp. (^{O}F)	·525	542	528	519
Carbon Conversion Eff. (%)	95.7	95.5	93.8	92.2
Boiler Eff. (%) (Heat-Loss Method)	77.5	77.6	76.9	76.0
Heat Loss Due to H_2O in Fuel (%)	3.55	3.55	3.53	3.51
Heat Loss from Burning Hydrogen in Fuel (%)	3.81	3.81	3.79	3.77

Table 5. Flue Gas Emissions in CWM Tests with Staged Combustion

Test Number	1	2	3	4
Flue Gas Analysis				
O_2 (%)	2.1	3.5	3.7	3.4
CO_2 (%)	15.8	14.5	14.5	14.5
CO (ppm)	81	74	92	124
SO_2 (ppm)	608	597	610	658
(lb/MMBtu)	1.10	1.19	1.20	1.28
NO_x (ppm)*	560	532	469	375
(lb/MMBtu)*	0.77	0.76	0.66	0.52
THC (ppm)	0.8	3.1	2.1	3.3
Particulate Emissions (uncontrolled)				
(lb/hr)	209	185	203	248
(lb/MMBtu)	7.37	6.33	7.01	8.33
C in Fly Ash (%)	48.9	40.7	50.4	53.3

*As ppm of NO + ppm of NO_2; calculated as lb of NO_2/MMBtu.

Table 6. Operating Conditions and Boiler Performance,
CWM Tests with Staged Combustion and Oxygen Enrichment

Test Number	1	2	3	4
O_2vol.% in Combustion Air	26.2	26.3	26.4	26.0
Overall Oxygen/Fuel Stoichio-Ratio	1.14	1.16	1.16	1.14
First-Stage Oxygen/Fuel Stoichiometric Ratio	1.14	1.02	0.88	0.76
Oxygen Injected (lb/hr)	1448	1505	1564	1433
Fuel Flow (lb/hr)	2871	2890	2949	2953
Steam Flow (lb/hr)	23330	23400	23660	23500
Thermal Input (MMBtu/hr)	30.32	30.65	31.77	31.99
Combustion-Air Temp. (^{O}F)	375	356	411	413
Total Air Flow (lb/hr)	18405	18872	19068	19143
Secondary-Air Flow (lb/hr)	12960	10910	8767	7263
Center-Tube-Air Flow (lb/hr)	4293	3638	2944	2389
Tertiary-Air Flow (lb/hr)	--	3166	6213	8299
Atomizing-Air Flow (lb/hr)	1152	1158	1144	1192
Atomizing-Air Pressure (psig)	130	130	131	130
Fuel Pressure at Burner (psig)	117	113	119	122
Avg. Flue Gas Temp. (^{O}F)	489	493	499	496
Carbon Conversion Eff. (%)	97.8	96.8	95.6	96.0
Boiler Eff. (%) (Heat-Loss Method)	82.8	81.8	81.0	81.3
Heat Loss Due to H_2O in Fuel (%)	3.54	3.54	3.50	3.48
Heat Loss From Burning Hydrogen in Fuel (%)	3.51	3.51	3.46	3.44

Table 7. Flue Gas Emissions in CWM Tests with Staged
Combustion and Oxygen Enrichment

Test Number	1	2	3	4
Flue Gas Analysis				
O_2 (%)	4.3	5.1	6.1	5.2
CO_2 (%)	19.7	19.0	18.5	18.3
CO (ppm)	64	77	64	79
SO_2 (ppm)	795	818	809	774
(lb/MMBtu)	1.18	1.25	1.25	1.21
NO_x (ppm)*	806	792	814	604
(lb/MMBtu)*	0.88	0.87	0.89	0.65
THC (ppm)	2.2	2.6	2.3	2.3
Particulate Emissions (uncontrolled)				
(lb/hr)	82	110	166	122
(lb/MMBtu)	2.70	3.59	5.23	3.81
C in Fly Ash (%)	44.1	47.8	44.5	55.2

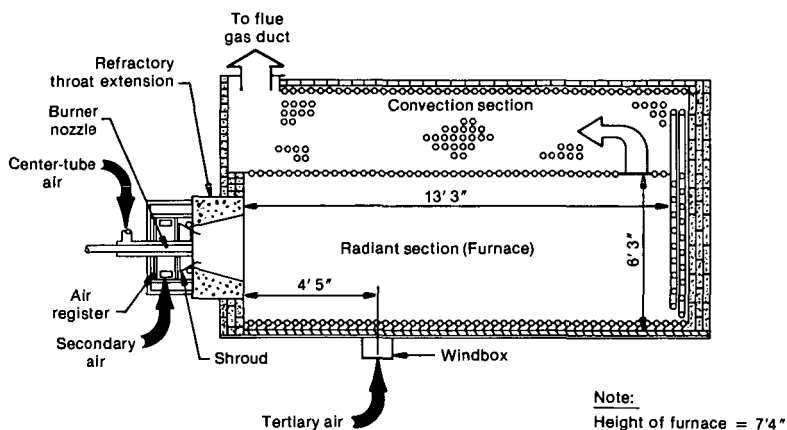*As ppm of NO + ppm of NO_2; calculated as lb of NO_2/MMBtu.

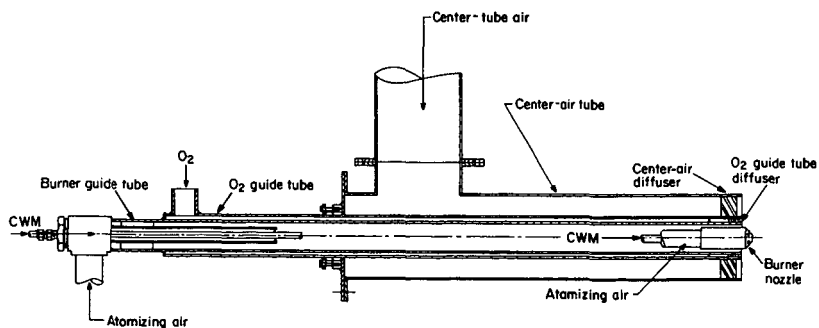**Figure 1. Horizontal cross-sectional view of 700-hp watertube boiler**

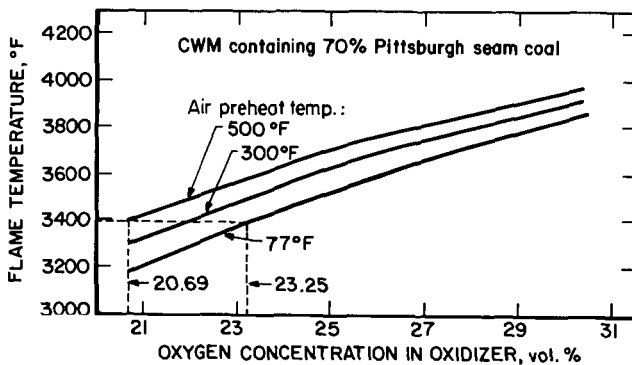**Figure 2. Burner used in oxygen enrichment tests**

Figure 3. Adiabatic CWM flame temperature with oxygen-
enriched air at various combustion air preheat
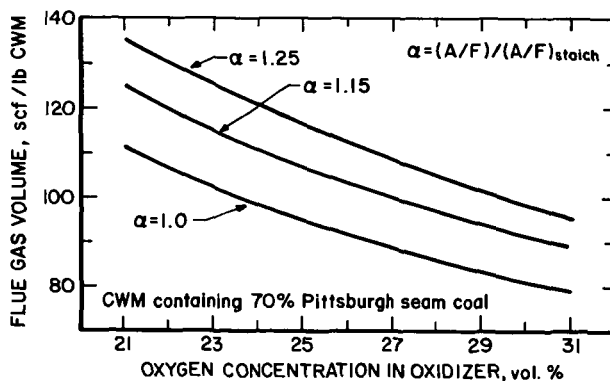temperatures (oxygen/fuel stoichiometric
ratio = 1.15)

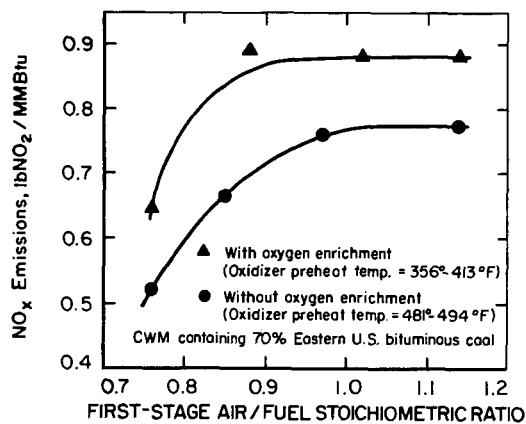Figure 4. Flue gas volume for CWM combustion with
oxygen-enriched air

Figure 5. Effect of Staged Firing on NO_x Emissions
(Overall oxygen/fuel stoichiometic ratio
≈1.15; full boiler load)